58

A new way to solve galloping on bundled lines

A concept, a prototype by two years field experience

J.L. Lilien
University of Liège, Belgium

P. Pirotte
University of Liège, Belgium

Tom Smart
Dulmison, U.K.

Marc Wolfs & Michel Escarmelle
Laborelec, Belgium

Introduction

Galloping is a large amplitude, low frequency, wind-induced oscillation of overhead lines. In the vast majority of cases, ice accretion is present on the conductor : this has the effect of modifying the conductor's cross-sectional shape such that it becomes aerodynamically unstable.

The **effects of galloping** on a line are dependent on the severity and duration of the event and on the type of line construction. Typical problems are : flashovers causing circuit breaker operation and arcing damage to conductors, including occasional conductor failure, infringement of clearance to ground, loosening and ejection of tower bolts, fatigue of tower steelwork during sustained events, conductor fatigue at tension strings, jumper fatigue, damage to spacers and stockbridge dampers, possibility of string failure, damage to conductor strands at suspension clamps and spacer clamps from fault current equalisation within the bundle.

This paper deals with a new type of anti-galloping device for conductors bundles, based on new research & development which takes into account the large experience obtained throughout the world after 60 years of galloping observations and many trials to solve the problem.

A global approach is presented including manufacturing and field testing A major challenge has been to produce a device whose optimum dynamic characteristics would not be affected by the onerous environmental conditions of a power line. Its basic function will consist of damping the torsional movement which governs most galloping cases.

The background research has been developed by the University of Liège over the last 5 years and has been presented at international symposia. [16, 17,18].

During last winter some promising results on line were obtained on a line in Belgium.

State-of-the-art

The mathematical translation of galloping mechanism is at the origin of the very first theory of galloping presented by Den-Hartog as early as 1930. [5]

Den-Hartog's approach takes only the aerodynamic properties of the ice profile into account. The mechanical characteristics of the system, conductor torsion in particular, are excluded from his analysis, at least as concerning aerodynamic effects. [13]

Introduction of torsion into the calculations considerably enriches the set of situations that favour galloping. Certain instances of galloping, including the case of spacered bundles, are hard to explain without it. There is no reason to exclude torsion since it participates, as does relative wind direction, in variations of that key parameter, the angle of attack. Having said this, we may point out that the Den-Hartog theory is far from obsolete, but it is only a special case in a more general theory that integrates the line's mechanical parameters.

Measurements carried out on real ice profiles [2, 6, 7, 9, 19, 21, 22, 23, 25, 27, 28, 29, 42] suggest that the Den-Hartog condition holds only for very slightly eccentric sheaths with lift properties opposite to those of more markedly eccentric profiles, at least for near-zero angles of attack (the vector joining the centres of gravity of sheath and conductor is nearly parallel to horizontal wind direction). This type of profile generally appears by freezing rain and its aerodynamic pitching moment coefficient is negligible.

To put things simply, the Den-Hartog theory is sufficient to explain the galloping of single conductors but not that of bundled conductors.

Lines in bundles

Bundled lines have a torsional stiffness [3, 6, 21, 43] that precludes significant rotation of the icy sheath during its formation. This produces a very eccentric sheath and thus makes Den-Hartog-type galloping very unlikely. However, *the natural vertical and torsional oscillation frequencies of spacered bundles are in the same narrow range*. This is not a chance occurrence due to line dimensions but *a structural mechanical property of bundles*. Under these conditions, despite torsional stiffness, a resonance phenomenon may cause vertical oscillation to excite torsion of sufficient amplitude and suitable phase to de-stabilize the system. The physical mechanism is similar in many ways to that which caused the collapse of the Tacoma bridge and to the "fluttering" of airplane wings, well-known to aerodynamics experts. [2, 4, 7, 8, 9, 15, 16, 17, 18, 19, 20, 24, 26, 31-40]

A way to avoid the problem has been suggested by the observation that, in Europe, single conductors are less sensitive than bundles to galloping. The generally-accepted explanation is based on the low torsional stiffness of single conductors (a few hundred Nm^2 for diameters below 35mm) as compared with that of conductors in spacered bundles, the latter being about 20-times greater than the former. Under the action of the wind (aerodynamic pitching moment) and the eccentric weight of the ice, this low degree of stiffness favours significant rotations as soon as a thin sheath appears on the conductor surface. Rotation of the sheath, as it forms, favours uniform thickness in the central area of the span, or at least produces a sheath with slight apparent eccentricity, with a diminished tendency to lift. So, the possibility of Den-Hartog galloping remains but any possibility of the much more frequent fluttering galloping is eliminated.

This is the origin of the idea to remove spacers (despacered bundles) [14], to use rotating clamp spacers or disks attached to each sub-conductor alternately (hoop spacers). Such procedures have provided some beneficial results but they are not without problems. First of all the problem inherent in single conductors: growth of thicker sheaths leading to static overloads. Moreover de-spacering is not practical for bundled lines with more than two subconductors whereas triple or quad conductors will be used more and more in the future due to the necessity to increase power transmission with limited environmental impact. Furthermore, rotating clamp spacers are subject to blocking and hoop spacers tend to be slowly damaged by glow conduction. As for unspacered bundles, they can come into contact as a result of transient overload currents (kissing) and later remain in contact.

In spite of these possible side effects, some operators have obtained industrially satisfying results, specially by removing spacers on twin bundles in well adapted conditions.

Another technique consists of installing interphase spacers to prevent any contact between phases; their action is only directed against the consequences of galloping and not against the real causes; the method also needs heavy masses to be added to the lines.

Some of the above actions have proven limited efficiency, but all have side effects and introduce new weak points.

Technical limitations of existing products :

We will limit our investigations to the most known devices up to day : the windamper [36](U.S.A) , the detuning pendulums [10,11,12] (Canada) and the GCD (galloping control device) [1,37] (Japan) :

The first one is limited to Den-Hartog galloping (thin ice shape with no aerodynamic pitching moment); if this condition seems to be met in some part of the USA, this is generally not the case in Europe where other meteorological conditions are more prone to favour the flutter galloping on bundle conductors. In Europe we also use more bundled conductors with small cross sections which may favour the flutter type of galloping.

The detuning pendulum only increases the torsional frequency and adds no damping to the phenomenon. This is an important limitation which requires a perfect design of the pendulums. This is generally not possible because ice conditions are not known at the design stage. Nevertheless this device has been widely used, with some success , mainly in Canada.

The GCD device increases the moment of inertia of a bundle line, without any effect on torsional stiffness and with negligeable damping. This is another type of detuning by decreasing torsional frequencies. The GCD is available in two versions. Similar comment as for the pendulum above.

These devices may be efficient in some circumstances but it is known that some overhead lines equipped with those systems have also galloped in some occurences.

The new device described here under (TDD - Torsional Damper and Detuner) will be a pure European product based on original idea, with new and attractive markets.

The expected industrial benefits are improved reliability of overhead lines hence reduction of outage, maintenance and repair costs, as well as possibility of line compaction with important decrease of construction cost.

A new concept : the Torsional Damper and Detuner (TDD)

We propose to combine a detuning effect with a high torsional damping. This has the major effect to negate the wind input energy to the line. The high level of damping increases the effectiveness of the device over a much larger range of frequencies and produces greater efficiency with lower masses than other systems.

Justification of the scientific background :

There is no way to explain in one page the complex theory of flutter galloping. This has been done in the literature by numerous authors [8,17,21,39]. The mechanism of galloping is very complex and the impact of torsional damping has not been well understood in the major part of the literature : some authors did not see the fundamental influence of torsional damping because there is no possibility to damp the galloping energy which is mainly in the vertical movement. But in fact torsional damping plays a key role on the angle of attack (position of ice eccentricity in relation with relative wind speed) hence preventing energy to be inputted on the line so that either instability is avoided or - for very high wind and big eccentricity - amplitude is sensibly reduced. So the combination of detuning (shifting between vertical and torsional frequencies), which avoids resonances, and torsional damping, which limits energy transfer, will solve the problem of flutter galloping. This is possible on overhead lines because the amount of torsional energy to be dissipated is rather low (some tenths of joules per span), which is possible with a compact device oscillating at a frequency close to 0.5 Hz adapted to the line.

Numerical simulations

Some results have been published in [15,16,17,18]. We generally adopt a 2 or 3 degrees of freedom model and we include the whole section of the line to be treated (i.e. all the spans between two anchoring towers are considered). Up to three loop galloping is considered. Both stability, limit cycle analysis and time response can be performed. Special attention has been devoted to take into account the bundle stiffness in an appropriate way. In fact we developed also a specific theory which takes into account the way of fixation of the conductors at the anchoring and suspension towers.

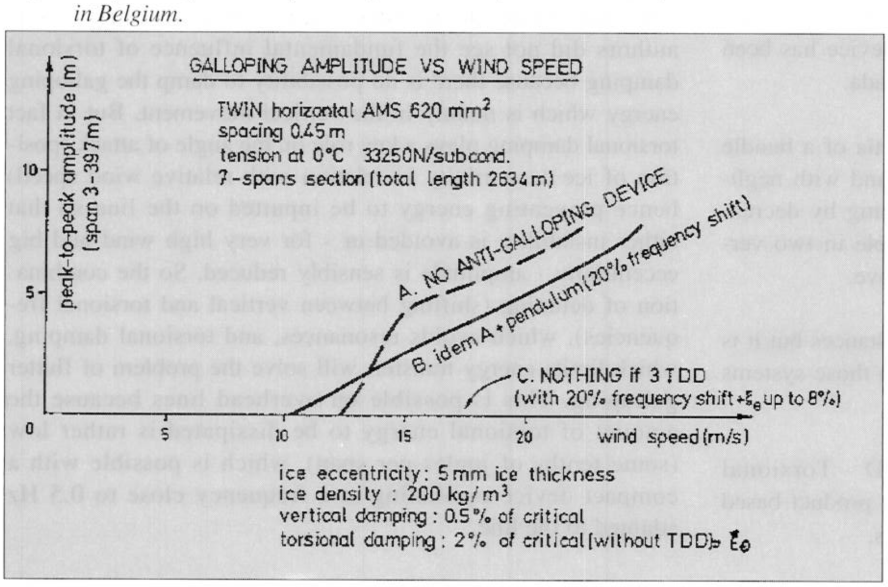
As ice shape is unknown we performed simulation with three basic ice shapes of increasing eccentricity (ice thickness from 1/6th of the conductor diameter to 1.25 the diameter). Ice density is between 200 and 900 kg/m³.

The computation is done for the full range of possible ice positions on the conductors (ice windward from the bottom to the top of conductor surface).

Wind-ranges is taken generally between 5 and 15 m/s.

Basic conductor properties are generally well known, except damping. For lack of information, vertical damping is taken as 0.5 % of critical damping (logarithmic decrement of 3%) and

Fig. 1 - Amplitude prediction for a 7 spans section (2x620 mm² AMS) in Belgium.



These damping acts in the frequency range of galloping (0.2 to 1 Hz). On bundled lines (where the vertical and torsional fretorsional damping is taken as 2% of critical damping (logarithmic decrement of 12 %).quencies are close together), it is un-important whether the damping is viscous or hysteretic.

Figure 1 shows a typical result for amplitude predictions and the corresponding effect of an appropriate TDD.

A prototype :

The work to transfer the theoretical parameters of mass, stiffness and damping into a practical device was undertaken by Dulmison (UK) Limited.

Experience in the design of other transmission line fittings (spacers, vibration dampers, etc...) was used in the design of prototype TDD devices.

The design process included the following stages :

1- definition of fabrication processes with production flexibility suitable for each set of theoretical parameters.

2- determination of pendulum mass, profile and dimensions for required stiffness, inertia and corona parameters.

3- design of a suitable structure to support the pendulum, allow the pendulum to pivot and to connect it to the bundled conductors.

4- design of a damping sleeve with suitable end connections to pendulum and end frames.

5- compounding of an elastomer for optimum damping and fatigue performance suitable for operation in the environment of an overhead electric power line.

Three different versions of a prototype TDD device were designed and manufactured :

- original prototype with fixed parameters
- second prototype with provision to change parameters
- third prototype from production tooling.

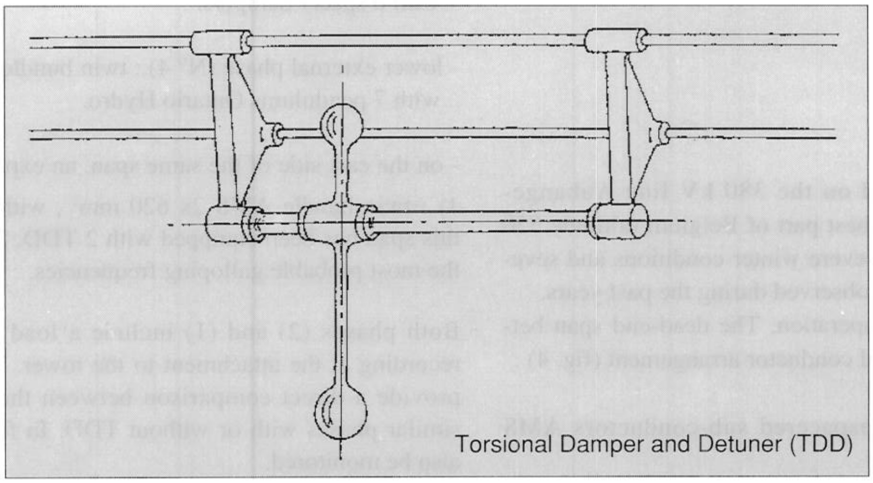
The first and second prototypes were hand-made but moulds and dies were producted in order to make the third prototype representative of a future production device and suitable for corona testing.

The pendulum for the first and second prtotypes was fabricated from threaded rod with cast iron spheres but the third stage prototype and all future production units was a single piece casting in solid zinc. This zinc alloy has the same density as cast iron and can be cast with an external profile suitable for corona free operation. It is also planned to use other lighter materials (aluminium) for the pendulum if the mass and corona requirements dictate a low mass with a large surface profile.

The expertise of a specialist rubber chemist was used to determine the optimum elastomer for energy extraction (damping) properties. Initially the damping sleeve was made of an elastomere containing 50% natural rubber and 50% butyl rubber. This was subsequently changed to a 100% butyl compound, with improved damping properties.

The general shape of the damper is illustrated here under. It consists of two frames fixed to the conductor bundle and supporting a rod with an external elastomeric cylinder. This is clamped at one end to the frame and driven in torsion at the other end by a balanced pendulum (fig. 2).

Fig. 2 - Diagramatic vue of the anti-galloping device (version for twin bundle)



Two years experience with TDD in Belgium

Mechanical test at the test station of LABORELEC

The test station consist of a very manageable 50 m. long, 4 m high dead-end span with adjustable tension and sag. Sensing and recording devices are provided.

The damper tests were conducted on a AMS 2x620 mm² cable bundle. The torsional vibration frequency was adjusted to ± 0.4 Hz (corresponding to a real value for real lines) by adding local torsional inertia. This ensures that the vertical movement (1 Hz) and torsional movement are decoupled, what makes observations easier.

The torsional movement is driven by frequency variable excitation (motor) . When standing wave is obtained, the excitation is released and the vibration gradually reduces through damping . A first test was conducted with the rotating part of the damper locked, making it without damping effect. The second test was conducted with the rotating part free to oscillate as in due operation : the damping increase is the consequence of the TDD action. The figure 3 clearly shows the TDD effect for a peak-to-peak 140° rotation amplitude of the rotating part. TDD effect on span energy dissipation increases with the square of the ratio between the TDD torsional amplitude and the span torsional amplitude (which is limited here to $(70/60)^2$)

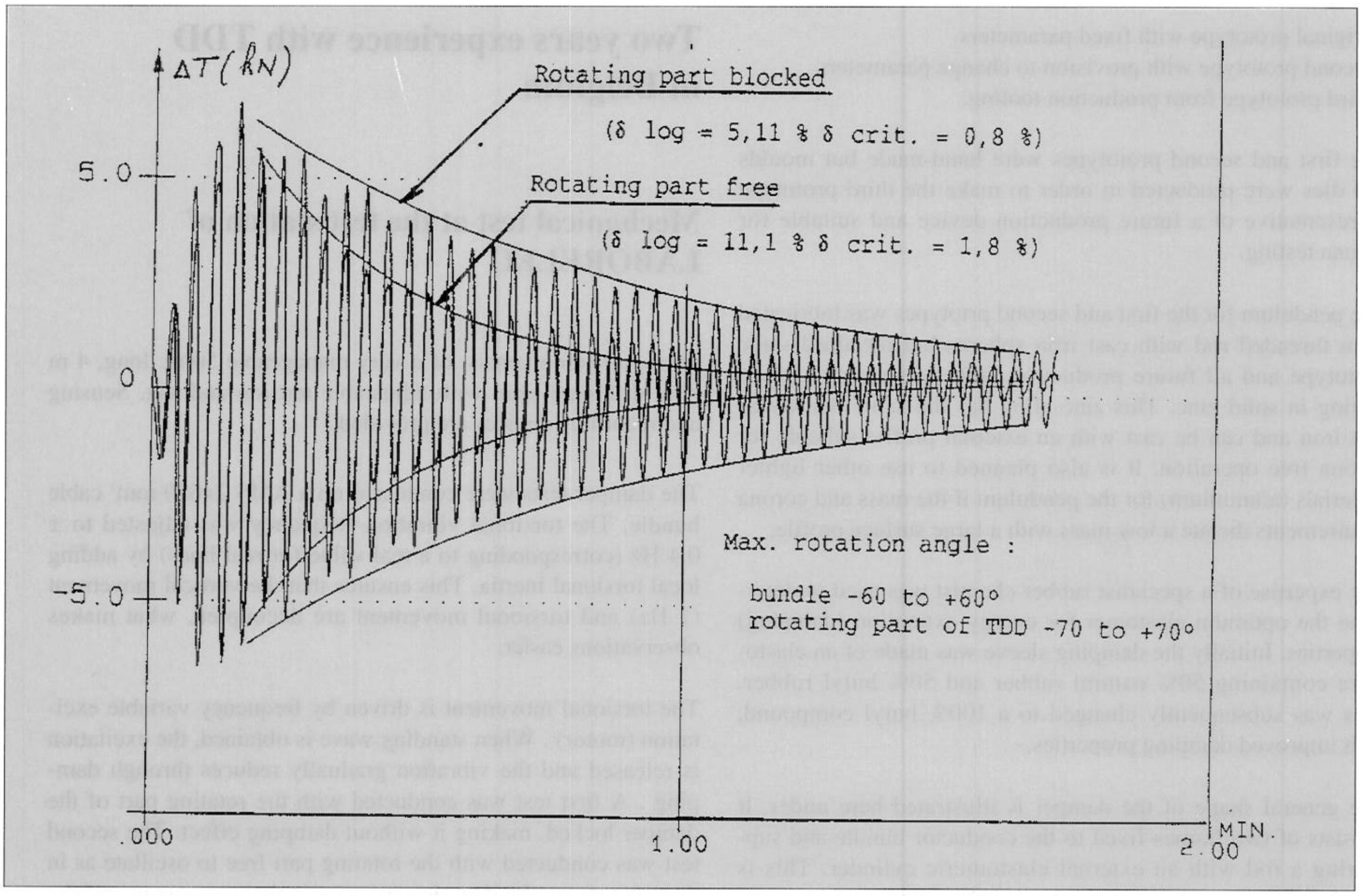


Fig. 3 - Damped torsional movement on Laborelec test span. The oscillogram is the recorded difference of tension between the two conductors of the twin bundle. Higher dissipation is obtained with TDD in movement.

Real line observations during winter 1992-1993

1) Field study

The observations occurred on the 380 kV line Aubange-Villeroux situated in the highest part of Belgium (altitude 550 m). This region is liable to severe winter conditions and several galloping cases had been observed during the past years. Only the west circuit is in operation. The dead-end span between towers 2-3 has a special conductor arrangement (fig. 4) :

- upper phase (N°3) : 2 despacered sub-conductors AMS 620 mm^2
- lower internal phase (N°2) : twin bundle AMS 2x 620 mm^2, with 6 spacer dampers.
- lower external phase (N° 4) : twin bundle AMS 2x 620 mm^2, with 7 pendulums Ontario Hydro.
- on the east side of the same span, an experimental phase (N° 1) : twin bundle AMS 2x 620 mm^2 , with 3 spacer dampers; this span has been equipped with 2 TDD. These were tuned to the most probable galloping frequencies.

Both phases (2) and (1) include a load sensor for tension recording at the attachment to the tower. These measurement provide a direct comparison between the behaviour of two similar phases with or without TDD. In future phase (4) will also be monitored.

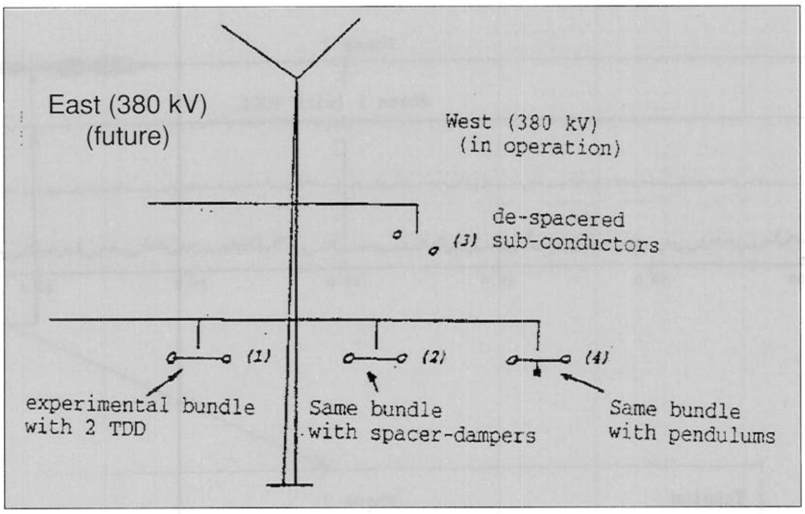


Fig.4 - Real line test span configuration in the Belgium Ardennes, near Villeroux.

2) Recorded vibrations

Two cases of large amplitude tension variations were detected by the recording station during the last winter, but only the first one corresponded to the usual galloping case with snow and moderate wind. The second case seemed to be due to longitudinal wind gusts. Both cases were very short (less than 40 minutes) and there were no visual observations. The following table gives a summary of the results.

These results leads to the conclusion that the tension amplitudes measured on the TDD protected phase are considerably lower than those of the non-protected one, due to the efficiency of the TDD's.

The time diagram of fig 5 clearly shows how the TDD really acts : from min. 5 to 25, the phase without TDD does not move while a regular but very limited vibration is observed on the phase with TDD This is the consequence of the TDD resonance : this TDD movement absorbs most of the inputted energy and prevents the wind energy transfer to vertical motion.

On the contrary, from min. 26 to 35, a large amplitude vibration is developing on the non-protected phase while the light movement of the protected phase progressively disappears.

Date	Meteorological conditions	Tension Vibrations		
		Vibrating phase	Frequency	Max. peak - peak tension amplitude
first case - 17/11/92 duration : 10 min. see figures : 5 to 6	wind speed : 18 to 40 km/h direction : 70° to line some gusts temperature: + 0.6°C light snow	(2) without TDD (1) with TDD	0.39 Hz 0.38 and 0.55 Hz	10 kN 1.3 kN
second case : 26/11/92 duration : 7 min. figures : 7 to 8	wind speed : 25 to 65 km/h direction : 45° to line heavy gusts temperature: +11°C	(2) without TDD (1) with TDD	0.44 Hz 0.08 - 0.41 Hz	6 kN 1.5 kN

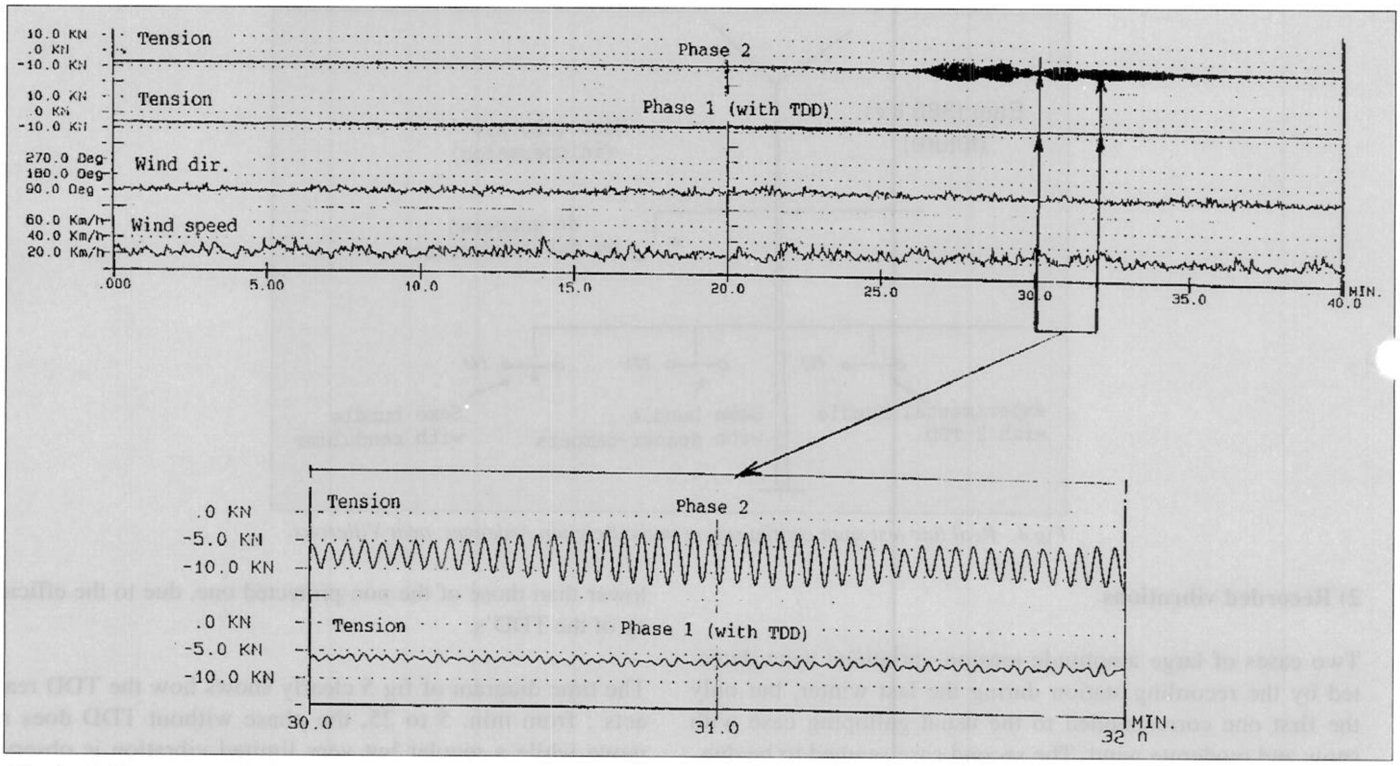


Fig. 5 - Galloping record 17/11/92, 8h10 GMT (T moy = 0.6°C)

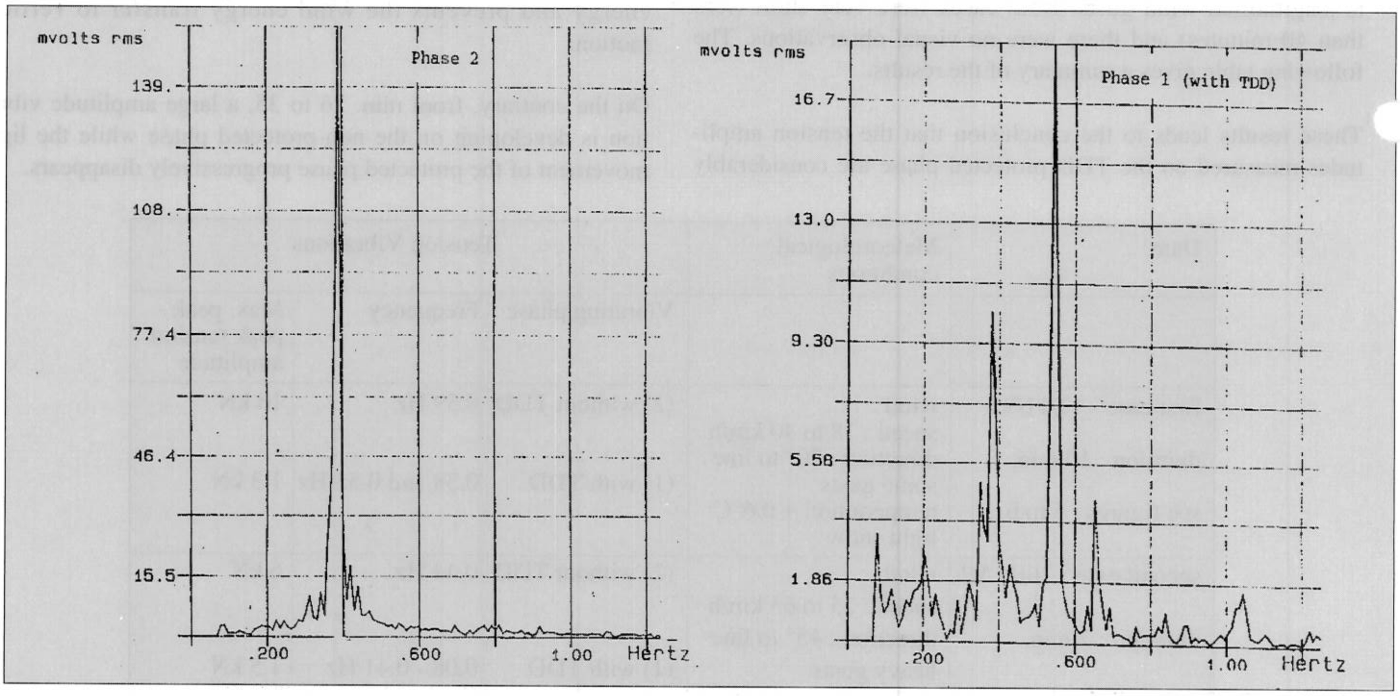


Fig. 6- Fourier analysis of the tensions recorded on 17/11/92 (min 30)

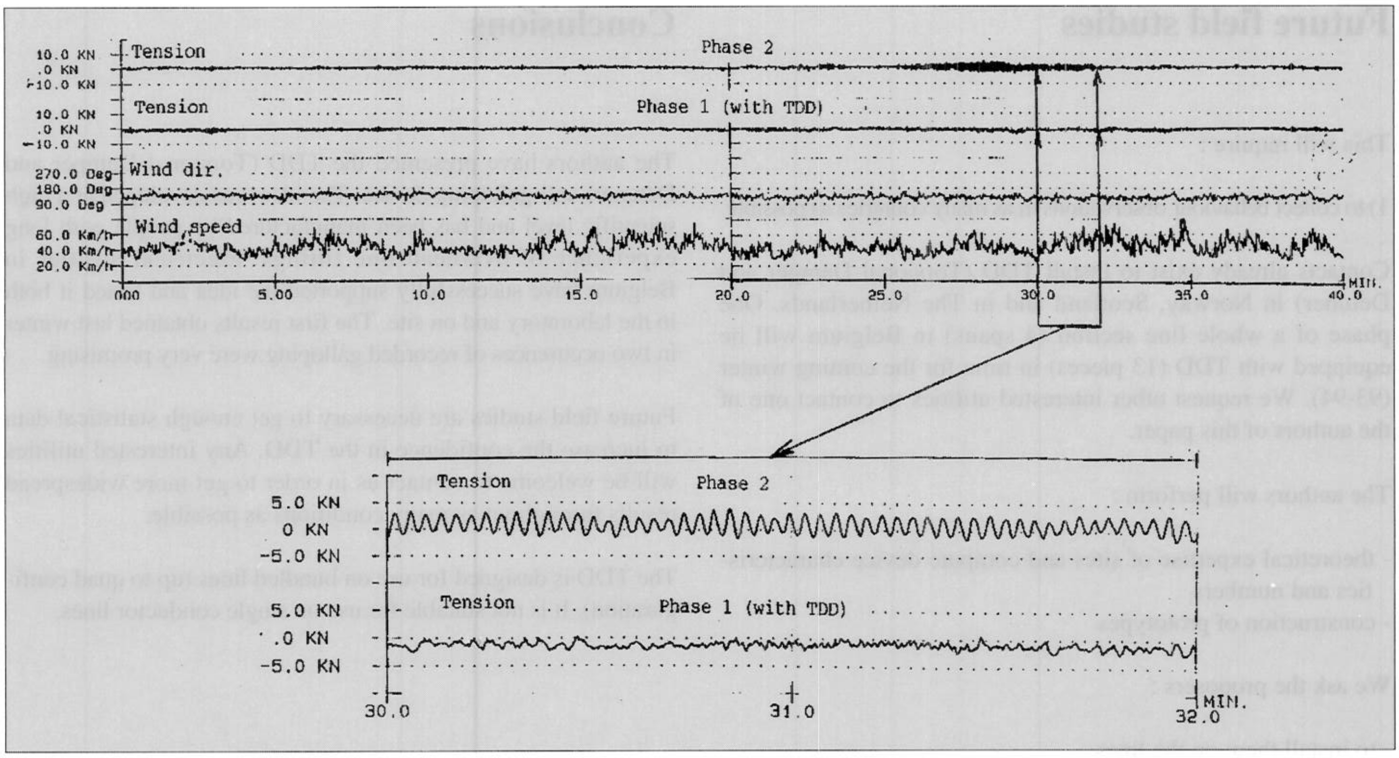


Fig. 7 - Vibration record 26/11/92, 1h13 GMT (T moy = 11°C)

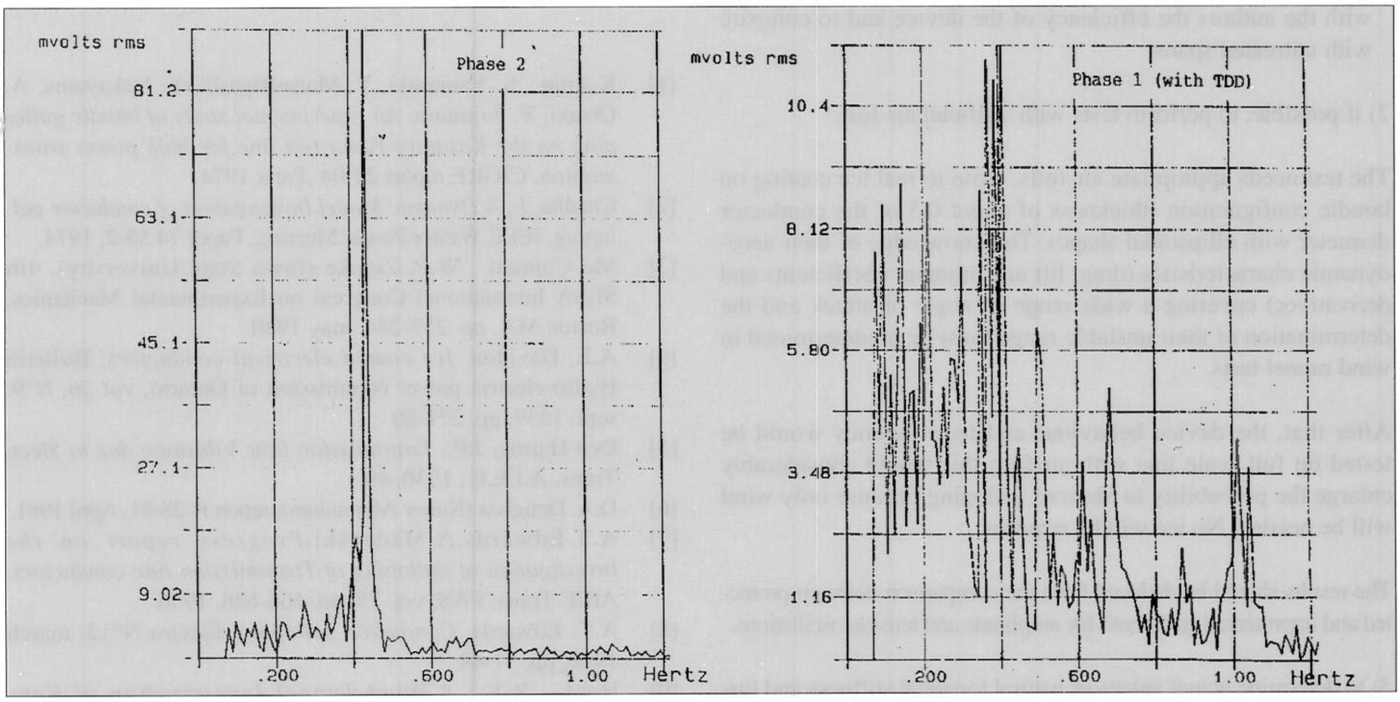


Fig. 8 - Fourier analysis of the tensions recorded on 26/11/92 (min 30)

Future field studies

This will require :

1) to collect behaviour observations in as many countries as possible.

Contacts already exist to install TDD (Torsional Damper and Detuner) in Norway, Scotland and in The Netherlands. One phase of a whole line section (4 spans) in Belgium will be equipped with TDD (13 pieces) in time for the coming winter (93-94). We request other interested utilities to contact one of the authors of this paper.

The authors will perform :

- theoretical expertise of sites and compute device characteristics and numbers
- construction of prototypes

We ask the proposers :

- to install them on the lines
- to collect informations.
- by means of visual observations or signal analyses, to study , with the authors the efficiency of the device and to compare with untreated spans.

2) if possible, to perform tests with artificial air-foil.

The test needs appropriate air-foils, close to real ice coating on bundle configuration (thickness of about 0.5 of the conductor diameter with ellipsoïdal shape). The knowledge of their aerodynamic characteristics (drag, lift and moment coefficients and derivatives) covering a wide range of angle of attack and the determination of their unstable range must be predetermined in wind tunnel tests.

After that, the device behaviour and its efficiency would be tested on full scale line with air-foil; this would considerably enlarge the probability to observe galloping because only wind will be needed. No ice will be required.

The results should be deduced from the comparison between protected and unprotected span, both for amplitude and tension oscillations.

3) to determine actual values of natural torsional stiffness and torsional damping for a practical situation (existing overhead lines)

Conclusions

The authors have presented the TDD (Torsional Damper and Detuner) anti-galloping device. The idea was developed at a high scientific level and has been manufactured by people with long experience of overhead line fittings. Electrical utilities in Belgium have successfully supported the idea and tested it both in the laboratory and on site. The first results obtained last winter in two occurences of recorded galloping.were very promising.

Future field studies are necessary to get enough statistical data to increase the confidence in the TDD. Any interested utilities will be welcome to contact us in order to get more widespread results throughout as many conditions as possible.

The TDD is designed for use on bundled lines (up to quad configuration). It is not suitable for use on single conductor lines.

References

[1] K.Anjo , S. Yamasaki, Y. Matsubayashi, Y. Nakayama, A. Otsuki, T. Fujimura. *An experimental study of bundle galloping on the Kasatory-Yama test line for bulk power transmission.* CIGRE report 22-04 ,Paris 1974.

[2] Chadha, J., *A Dynamic Model Investigation of conductor galloping.* IEEE Winter Power Meeting, Paper 74 59-2, 1974.

[3] Mc Connell , W.P. Zemke (Iowa State University). 4th SESA International Congress on Experimental Mechanics, Boston MA, pp. 237-244, may 1980.

[4] A.E. Davidon. *Ice coated electrical conductors.* Bulletin Hydro-electric power commission of Ontario, vol 26, N°9, sept. 1939, pp. 271-80

[5] Den Hartog, J.P., *Transmission Line Vibration due to Sleet*, Trans. A.I.E.E., 1930, 49.

[6] D.A. Douglass (Kaiser Aluminium). report R-28-81, April 1981.

[7] A.T.Edwards,A.Madeyski.*Progress report on the Investigation of galloping of Transmission line conductors.* AIEE Trans, PAS, vol. 75, pp. 666-686, 1956

[8] A.T. Edwards. *Conductor galloping.* Electra N°12, march 1970, pp. 31-48

[9] Hack , R.K., *A Wind Tunnel Investigation of Four Conductor Models with Simulated Ice*, NLR TR 81O76L,

Netherlands, NLR, 1981.

[10] D.G. Havard, J.C. Pohlman. *Field testing of detuning pendulums for controlling galloping of single and bundle conductors*. IEE paper A79 499-5, Vancouver, Canada, july 1979

[11] D.G. Havard. Ontario Hydro EPRI research program RP-1095, 1980.

[12] D.G.Havard, J.Pohlmann. IEEE Trans PAS, vol. 103, n°2, pp. 318-327, 1984

[13] J.C.R. Hunt , D.J.W. Richard. *Overhead line oscillations and the effect of aerodynamic dampers*. IEEE Trans on PAS, vol 116, N°11, nov 1969, pp. 1869-74

[14] P.H. Leppers, H. Brand, M. Couvreur, M. Maljean. *Spacers removed to combat galloping*. Electrical world, vol. 187, N°9, may 1977, pp. 70-2

[15] J.L. Lilien, J.P.Ponthot. *Overhead lines galloping - modelisation*. Modelling and simulation of Electrical machines and Power systems, Elsevier Science Publishers, North-Holland, Imacs 1988, pp. 103-110

[16] J.L.Lilien, H. Dubois. *Overhead line vertical galloping on bundle configurations : stability criterions and amplitude prediction*. IEE Overhead line design and construction : theory and practice (up to 150kV), nov. 1988, Proceedings, pp. 65-69

[17] J.L. Lilien, H. Dubois, F. Dal Maso, *General mathematical formulation for overhead line galloping*. AIM study day on galloping, march 10, 1989.

[18] J.L. Lilien.*Galloping and compact line*. CIGRE symposium on compacting overhead transmission lines, Leningrad, june 1991, report 200-01

[19] Mukhopadhyay, V., *The Galloping Oscillations of Square Section Cable Suspended in a Smooth Wind Flow*, Jour. Ind. Aerodyn. 5 [1979] 35-51, Amsterdam, Printed in the Netherlands.

[20] Nakamura, Y., *Galloping of Bundled Power Line Conductors*. Journ., Sound & Vibration, 73 [3], pp. 363-377, 1980.

[21] O. Nigol, Clarke, G.J., *Conductor Galloping & Control Based on Torsional Mechanism*, IEEE C-74 116-2, Conference Paper, 1974.

[22] O.Nigol, G.J.Clarke, D.G.Havard. IEEE Trans PAS, vol. 96, n°5, sept. 1977, pp. 1666-1674

[23] O.Nigol, P.G.Buchan. IEEE Trans PAS, vol 100, n°2, 1981

[24] Novak, M. *Galloping Oscillations of Prismatic Structures*, A.S.C.E. Journ. Engrg. Mech. Div., vol. 98, Feb. 1972.

[25] A. Otsuki, O. Kajita. *Galloping phenomena of overhead TRansmission lines*. Fujikura technical review, N°7, 1975, pp. 33-46

[26] Ottens, H.H., *Some Theoretical Considerations on the Effect of Cable Torsion on Gallop* NRL, Netherlands, NRL TR 81003 L, July 22, 1980.

[27] Parkinson, G.V., *Aerolelastic Galloping in One degree of freedom*, Op. Cit. paper 23, p. 582.

[28] Ratkowski, J.J., *Experiments on Galloping Spans*, Trans, IEEE, vol. 82, pp. 661-669.

[29 C.B. Rawlins K.R. Greathouse, R.E. Larson. *Conductor vibration - A study of field experience*. AIEE Conference paper CP61-1090, oct 1961

[30] C. B. Rawlins. *Analysis of conductor galloping field observations — singles conductors*. IEEE paper 81 WM0538, 1981.

[31] Richardson, A.S., *Some Effects of conductor Twisting on Galloping*, IEEE Summer Power Meeting, Vancouver, B.C., 1979, Trans, IEEE Power Apparatus & Systems, PAS-99, 1980, p. 811.

[32] Richardson, A.S., *The Time Line Method for Assessing Galloping Exposure*, IEEE/PES Paper 82-WM-083-4, New York, Jan/Feb. 1982, paper.

[33] Richardson, A.S., *Predicting Galloping Amplitudes*, A.S.C.E., Journ. Engng. Mech., vol. 114, n° 4, Apr. 1988, p. 716.

[34] A.S. Richardson, J.L. Lilien, H. Dubois. *Predicting galloping fatigue cycles in quad bundles*. CIGRE 1990 - report 22-102.

[35] A.S. Richardson, J.R. Martucelli, W.S. Price. *Research study on galloping of electric power transmission lines*, paper 7, 1st Symposium on Wind effects on Buildings and Structures, Teddington, England, june 1963, p. 612

[36] A.S. Richardson. *A study of galloping conductors on a 230 kV Transmission line*. Electric power systems research, (2151991) 43-55

[37] S. Sasaki, M. Komoda, T. Akiyama, M. Oishi, Y. Kojima, T. Okumura, Y. Maeda. *Developments of galloping control devices and its operation records in Japan*. Cigre report 22-07, 1986 session.

[38] Scruton, Christofer, *On the Wind Excited Oscillations of Stack, Towers and Masts*, paper n°16, National Physical Laboratory, vol. II, Symposium June 26-28th, 1963, p. 798.

[39] T.J. Smart et al, "*Galloping Suppression Tests on Overhead Lines*", CIGRE paper 22-03, Paris, August 1986

[40] T.J. Smart, "*Design Criteria and Performance Requirements of Vibration Control Devices for use on Overhead Power Lines*", BEAMA Technical Seminar, Saudi Arabia, January 1992

[41] Transmission line reference book. *Wind induced conductor motion*. Electric Power Research Institute, Palo Alto, CA, 1980, chapter 4

[42] Tunstall, M., Koutselos, L.T., *Further Studies of the Galloping Instability & Natural Ice Accretions on Overhead Line Conductors*, 4th Int. Conf. on Atmospheric Icing of Structures, Paris, sept.1988.

[43] M. Wolfs (LABORELEC), AIM Study day on Galloping (§2). Liège, March 1989.

[44] M. Escarmelle, *Etat actuel des mesures mécaniques sur la ligne expérimentale à LABORELEC*, LABORELEC MO2-300-93-002, janvier 1993.

[45] M. Escarmelle, *Galop des lignes haute tension (hiver 1992-1993), Villeroux*, LABORELEC MO2- 300-93-003, février 1993.